Magnetic Control of Fermilab Switchyard Beam Splits

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ABSTRACT

A “four-bump” set of magnets is proposed for the Fermilab Switchyard to control relative intensity between the Meson and Neutrino-Muon beamlines. Control currently relies on moving the electrostatic septa that split the beam, which can add to setup time and complications when experiments request frequent intensity changes. Furthermore, movement of the septa can increase beam loss on the downstream Lambertson magnet. By magnetically bumping the beam to change the split ratio, consistent alignment of the beam shadow and Lambertson septum can be achieved over the desired intensity range.

Introduction

Overview of SY120

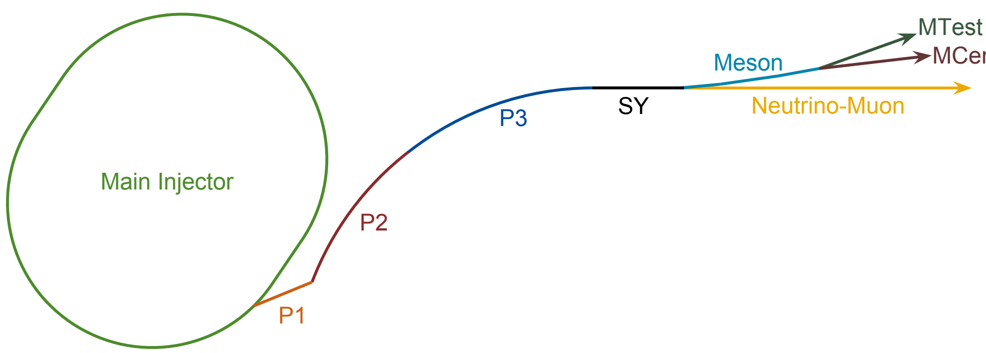

Figure 1. Overview of the Fermilab SY120 Fixed Target beam lines.

The Fermilab Fixed Target program (a.k.a. ”SY120”) currently supports three users: two Fermi Test Beam users in the Meson beamline, and the SeaQuest experiment in the Neutrino-Muon (NM) line. 120 GeV proton beam is provided via resonant extraction from the Main Injector synchrotron, and thus the beam must be split twice to serve all three users simultaneously. The proposal in this paper will focus on the first split between Meson and NM, but can also be adapted for the second split in the Meson line.

Both Meson users request specific beam intensities, with the remainder going to the NM line. Because of the variability of intensity requests for the Meson line, the intensity ratio between Meson and NM must be easily and consistently adjusted to meet the needs of the experiments. Furthermore, the split adjustment method must not cause excessive beam loss that would limit available beam intensity.

Electrostatic septa are used in the Fermilab Switchyard to split beam from the Main Injector to the Neutrino-Muon line and to the Meson line. The electrostatic septa that provide the split between Meson and NM are known as the ”MSeps”. A simple diagram of an electrostatic septum is displayed in Figure 2.

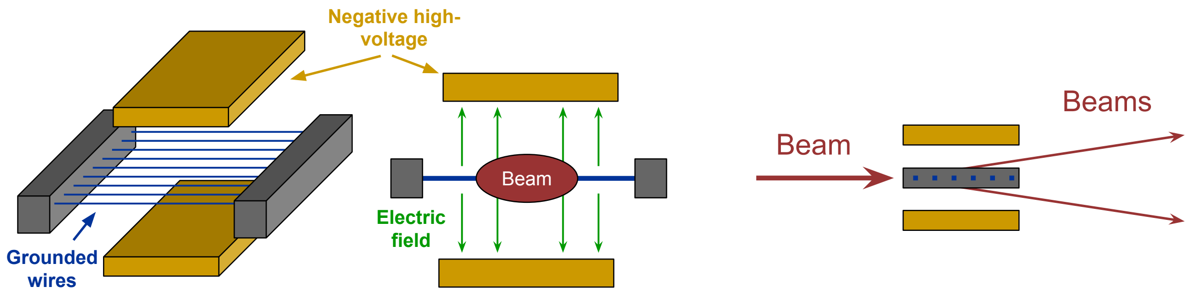

Figure 2. Electrostatic septum for beam splitting.[1]

Intensity requests for each line are highly asymmetric, with the vast majority of beam going to the SeaQuest experiment in the Neutrino-Muon line. The MTest and MCenter test beam areas request a variety of intensities, so the relative split between Meson and Neutrino-Muon must be easily changed with minimal beam loss.

The current method of adjusting the intensity ratio between Meson and Neutrino-Muon beamlines involves physically moving the MSeps using stepper motors. Operators type the desired position in mils of the grounded wires into the F:MSEPAL ACNET parameter, and stepper motor controllers convert the necessary move to steps before carrying out the command.

A setting of 0 mils on F:MSEPAL corresponds to a 50-50 intensity split between Meson and Neutrino-Muon, assuming beam is centered in the beam pipe. When both beamlines are running, F:MSEPAL is typically set to between 165 and 400 mils to accommodate Meson experiment intensity requests[1]. When SeaQuest is the only user of the beam, F:MSEPAL is set to greater than 420 mils to send all beam down the Neutrino-Muon beamline.

Deflection angle from septa

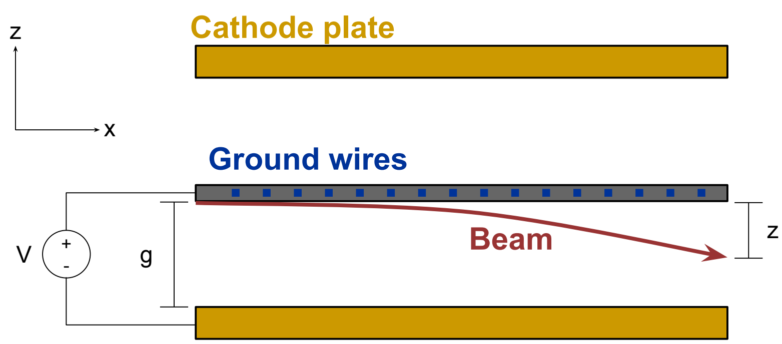

Figure 3. Diagram of variables for calculation the deflection angle from the electrostatic septa.

Figure 3 shows the deflection of the proton beam through one side of the electrostatic septum. To calculate the displacement of the beam due to interaction with the septum's electric field over its length, we first write the relativstic version of Newton's Second Law:

$$F_z = \frac{dp_z}{dt} = \frac{d}{dt}(\gamma m v_z) \tag{1}$$

The Lorentz force due to the septum's electric field is $F_z = qE_z = q\frac{V}{g}$, where V is the power supply voltage for the septum. So we have:

$$\frac{d}{dt}(\gamma m v_z) = q\frac{V}{g} \tag{2}$$

Integrating both sides of Equation with respect to time,

$$\int \frac{d}{dt}(\gamma m v_z)dt = \int q\frac{V}{g}dt \tag{3}$$

[1] In fact, the maximum allowed beam intensity for Meson is much lower than what is allowed for Neutrino-Muon, so an asymmetric intensity split is always required.

Yields the following:

$$\gamma m v_z = \frac{qV}{g} t \tag{4}$$

Solving for v_z and integrating again with respect to time yields:

$$z = \frac{qV}{2\gamma m g} t**2 \tag{5}$$

Since longitudinal velocity $v_x = \frac{x}{t}$, we know that $t = \frac{x}{v_x} = \frac{L}{\beta c}$ for total septum length L and longitudinal velocity $v_x = \beta c$. Substituting into :

$$z = \frac{qVL^2}{2\gamma m g \beta^2 c^2} \tag{6}$$

The effective angle imparted by the beam by passing through the septum is $\theta = tan^{-1}[\frac{z}{L}]$. In the small angle approximation, $\theta = \frac{z}{L}$. The proton rest mass $mc^2 = 938MeV$, with fundamental charge of $q = e = 1.602E-19$ Coulombs.

So the angle imparted by the septum is:

$$\theta = \frac{VL}{2\gamma g \beta^2} \frac{1}{938e6} \tag{7}$$

For 120 GeV beam, $\gamma = \frac{E_{total}}{E_{rest}} = \frac{120e9}{938e6} = 127.9$, and $\beta = 0.99997$. The operational voltage of the MSeps is 87 kV, the gap between grounded wire and the cathode is 2 cm, and $L = 2*3.048$ m since we use two septa together. Thus the bend angle from the MSeps is $\theta = 0.1105$ milli-radians.

High MLAM losses

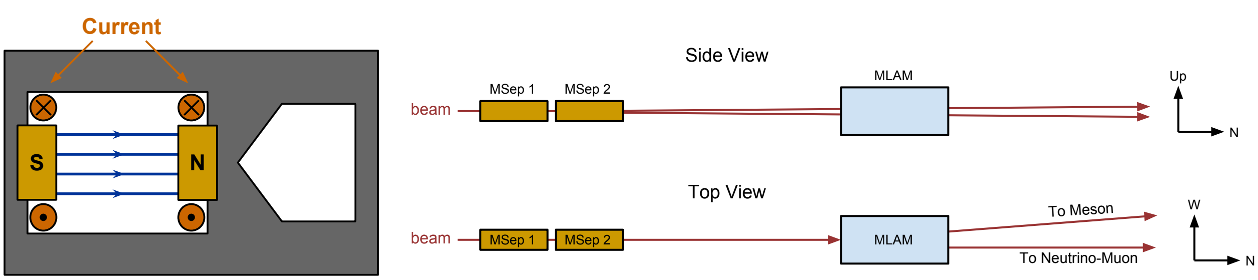

Figure 4. Lambertson magnet in conjunction with electrostatic septa for beam splitting.

To provide the necessary beam separation between the Meson and NM beamlines, a Lambertson magnet called MLAM is used in conjunction with the MSeps. Pictured on the left in Figure 4, a Lambertson is a two-aperture magnet; one aperture is field-free, and the other provides a dipole field.[1] The field region of the Lambertson bends perpendicular to the split from the electrostatic septa. Pictured in the right of Figure 4, the MSeps split the beam vertically so NM beam coasts straight through the field-free region of MLAM, and Meson beam is bent West toward the rest of the Meson line.

The region in the Lambertson between apertures, known as the "septum", can cause high losses if struck by beam. However, the location of the "shadow" between beams is determined by the position of the MSep wires. To avoid beam loss on the MLAM septum, the MSep wire position must line up with the MLAM septum. Herein lies the main problem with the current method of split control: MLAM septum losses increase as more beam is split to Meson, because moving the MSep tanks makes the split asymmetric with respect to the Lambertson septum.

This asymmetry is corroborated by plotting historical data for the loss monitor on the upstream face of MLAM as a function of MSep position. Pictured in Figure 5, it is apparent that beam loss increases as more beam is split to Meson (i.e. as MSEPAL is reduced). Thus any solution to the MLAM loss problem must preclude movement of the MSep tanks that will lead to an asymmetry with respect to MLAM's geometry. Based on the historical loss monitor data in Figure 5, it is very likely that the MSeps and MLAM are aligned as pictured in Figure 6: MLAM losses are lowest when all beam goes to NM, and increases as more beam splits to Meson. Further study of alignment data is required to verify this.

This Lambertson septum loss represents the largest impediment to the operation of certain modes required by Meson Test users. As a test beamline for detector research and development, Meson Test is able to provide a variety of particle species and energies to the test hall. However, the yield for certain energy modes is very low, and thus the primary proton beam must be near maximum allowed intensity to provide enough secondary particles. Often, exceedingly high losses on MLAM prevent Operators from sending the necessary intensity to the Meson line to meet the experiment's needs. If this loss can be addressed, it will remove a significant impediment to Fermi Test Beam Facility's ability to conduct detector research and development at low energy (several GeV).

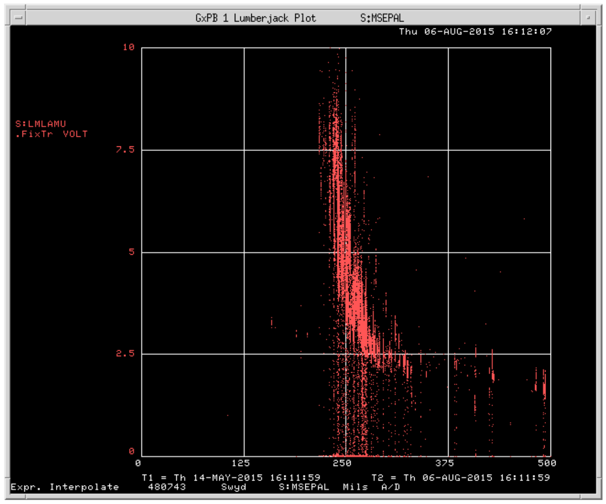

Figure 5. Datalog plot showing upstream MLAM losses vs. septum position: losses are higher when more beam is split to Meson.

Beam split simulation

The following section shows particle-tracking simulations for the current beam splitting method, and compares the results to a simulation of the proposed method to address the MLAM losses. Simulation is handled by custom Python code and uses dimensions and beam characteristics based on survey data in Enclosure B.[2] Beam width is determined from wire chamber measurements,[3] and divergence is estimated to be 1% of the beam width. Grey boxes in the figures represent the apertures and dimensions of the electrostatic septa and Lambertson magnet.[45]

Movable electrostatic septa

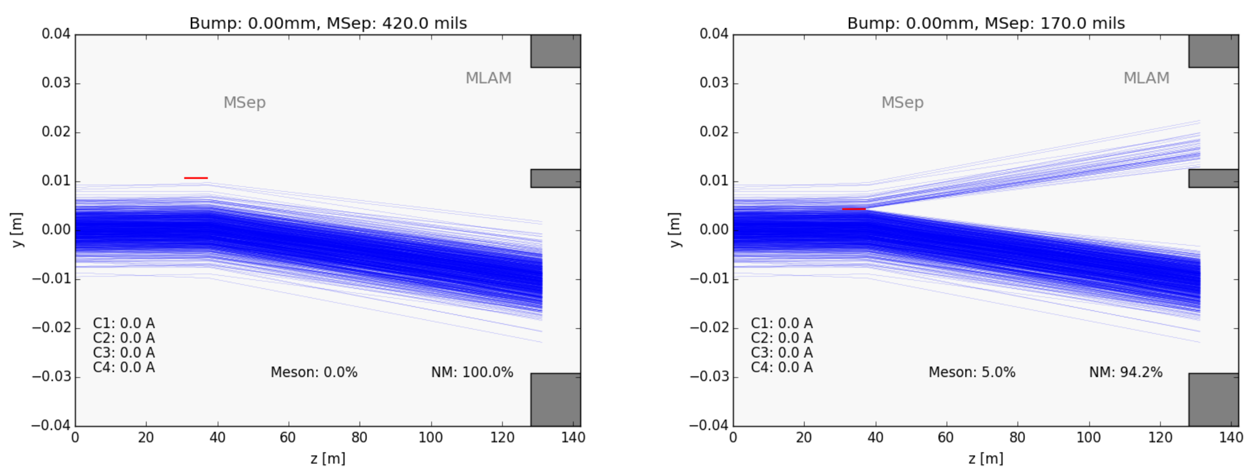

Figure 6. Current split method using movable electrostatic septum.

Figure 6 demonstrates particle trajectories for two situations: all beam to Neutrino-Muon, and beam to Neutrino-Muon plus the maximum-allowed beam to Meson. Each blue track represents one particle trajectory, and the red line

It is apparent that moving the MSep wires to split beam to Meson alters the symmetry between the beam split and the septum of MLAM. In fact, as the wires are lowered (i.e. F:MSEPAL goes down), the upper beam moves closer to the MLAM septum. This corroborates the data from Figure 5 that shows upstream MLAM losses increasing as F:MSEPAL increases.

Furthermore, movement of the MSeps present other practical issues that lead to beam loss and increased setup time. Each septum uses an upstream and downstream stepper motor to control the position and angle of the tank. Continued movement of the septa contributes to wear of the mechanical parts of the system, and there is noticeable hysteresis in terms of setting and eventual position of the motors. Each significant move requires considerable ”fine tuning” to achieve the desired split ratio with minimized beam loss.

Proposed split method

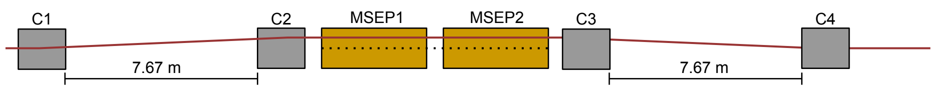

Figure 7. Overview of proposed 4-bump.

The proposed solution to improve MLAM losses is to leave the MSeps in a fixed position so the grounded wires line up with the septum of MLAM. To change the split ratio between Meson and NM, four dipole trims will bump the beam in a ”four-bump” configuration to change the average beam position through the MSeps. The first two dipole trims will set the desired position and angle across the MSeps, and the final two downstream of the septa will allow for control of the position and angle on MLAM without changing the split percentage.

Pictured in Figure 7, the four-bump will allow for precise adjustment of the split ratio while also providing control over the split symmetry with respect to MLAM. In other words, the ”shadow” between split beams can be tuned to always line up with the MLAM septum, and the location of the MSep grounded wires will not change.

Figure 8 illustrates the proposed two-bump with the same particle tracking simulation used for Figure 6. It is clear that moving the beam instead of the MSeps provides more clearance for the beam to miss the MLAM septum, thus reducing beam loss. Furthermore, the current in the two correctors downstream of the septa can fine-tune the position and angle of the beam at MLAM. Thus the four-bump will decouple the beam split ratio from the position and angle going into MLAM; both will be tuned independently to achieve ideal trajectory and intensity to both beamlines after the split.

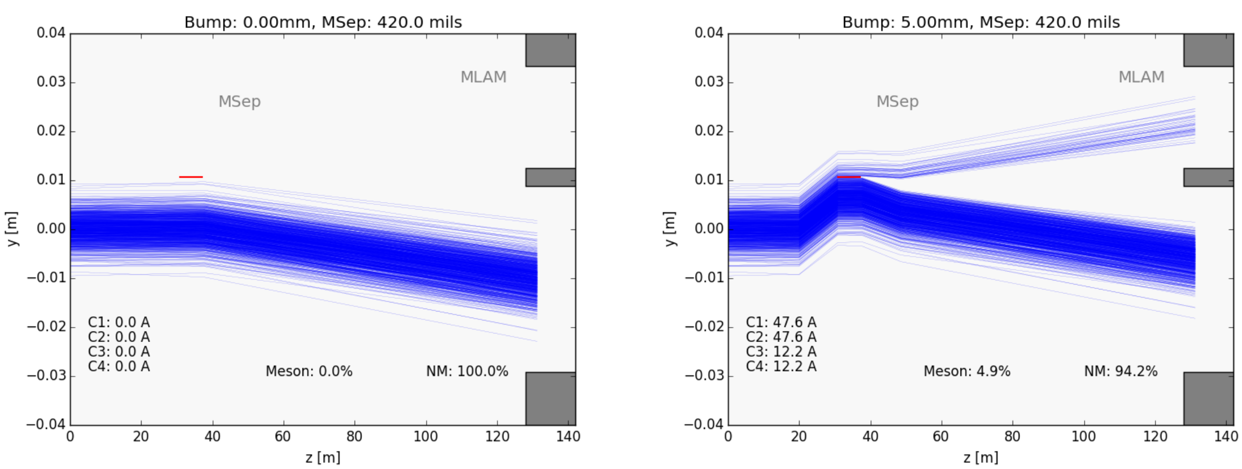

Figure 8. Proposed split method using beam two-bump, showing all beam to Neutrino-Muon (left) and splitting maximum beam to Meson (right).

Estimation of magnet currents

To estimate the magnet currents required for the available EDTB dipoles, the relationship between beam position at the MSeps and corrector angles is derived using Courant-Snyder parameters from a TRANSPORT simulation of the beamline.

Let θ_1 and θ_2 represent the beam deflection angles at C1 and C2 correctors respectively. Also let M represent the transfer matrix between correctors such that:

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' + \theta_1 \end{pmatrix} \tag{8}$$

$$where \quad \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}[\alpha_1 sin(\phi_{12}) + cos(\phi_{12})] & \sqrt{\beta_2\beta_1} sin(\phi_{12}) \\ \frac{1}{\sqrt{\beta_2\beta_1}}[(-\alpha_2+\alpha_1)cos(\phi_{12}) + (\alpha_2\alpha_1+1)sin(\phi_{12})] & \sqrt{\frac{\beta_2}{\beta_1}}[-\alpha_2 sin(\theta_{12}) + cos(\theta_{12})] \end{pmatrix} \tag{9}$$

Similarly, the transfer relationship between C2 and the point m between the MSeps is:

$$\begin{pmatrix} x_m \\ x_m' \end{pmatrix} = \begin{pmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{pmatrix} \begin{pmatrix} x_2 \\ x_2' + \theta_2 \end{pmatrix} \tag{10}$$

$$where \quad \begin{pmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_m}{\beta_2}}[\alpha_2 sin(\phi_{2m}) + cos(\phi_{2m})] & \sqrt{\beta_m\beta_2} sin(\phi_{2m}) \\ \frac{1}{\sqrt{\beta_m\beta_2}}[(-\alpha_m+\alpha_2)cos(\phi_{2m}) + (\alpha_m\alpha_2+1)sin(\phi_{2m})] & \sqrt{\frac{\beta_m}{\beta_2}}[-\alpha_m sin(\theta_{2m}) + cos(\theta_{2m})] \end{pmatrix} \tag{11}$$

Assuming that beam is centered and has zero angle entering the MSeps, $x_1 = 0$ and $x_1' = 0$. Solving Equation 8 for x_2 and x_2',

$$x_2 = M_{12}\theta_1 \quad and \quad x_2' = M_{22}\theta_1 \tag{12}$$

Solving Equation 10 for x_m and x_m' and substituting the above expressions for x_2 and x_2',

$$x_m = (N_{11}M_{12} + N_{12}M_{22})\theta_1 + N_{12}\theta_2 \quad and \quad x_m' = (N_{21}M_{12} + N_{22}M_{22})\theta_1 + N_{22}\theta_2 \tag{13}$$

For simplicity of notation, let $A = N_{11}M_{12} + N_{12}M_{22}$ and $B = N_{21}M_{12} + N_{22}M_{22}$. The dogleg needs to move only the beam position, so the beam angle through the MSeps should be 0. In other words, $x_m' = 0$. Setting the above expression for x_m' equal to zero and solving for θ_1 and θ_2,

$$\theta_1 = \frac{x_m}{A - \frac{N_{12}}{N_{22}}B} \quad and \quad \theta_2 = -\frac{Bx_m}{N_{22}A - N_{12}B} \tag{14}$$

TRANSPORT simulation of the beamline provides an estimate of the Courant-Snyder parameters necessary to finish the computation. From the simulation, we have $\beta_1 = 169.84$, $\beta_2 = 177.84$, $\beta_m = 181.07$, $\alpha_1 = -0.33686 * (2\pi)$, $\alpha_2 = -0.40730 * (2\pi)$, $\alpha_m = -0.43253 * (2\pi)$, $\phi_{12} = 0.00985$, and $\phi_{2m} = 0.00341$. Substituting these values into the above expressions for θ_1 and θ_2,

$$\theta_1 = 0.1171 x_m \quad and \quad \theta_2 = -0.1174 x_m \tag{15}$$

The angle due to a dipole field is $\theta = \frac{B'l}{(B\rho)}$ where B' is the magnetic field in $[T/m]$, l is the magnet length in $[m]$, $(B\rho)$ is the beam rigidity in $[Tm]$. The EDTB diple correctors have a transfer function of $Z = 0.00495\ [T/A]$ and length $l = 0.889\ [m]$,[6] so the current in each corrector is:

$$I_{C1} = \frac{\theta_1(B\rho)}{Zl} = 0.1171\frac{(B\rho)}{Zl}x_m \quad and \quad I_{C2} = \frac{\theta_2(B\rho)}{Zl} = -0.1174\frac{(B\rho)}{Zl}x_m \tag{16}$$

The particle-tracking simulation in the previous section shows that the beam position at the MSeps needs to be about 6.5mm to send the maximum allowed intensity to Meson. This corresponds to corrector currents of $I_{C1} = 47.6$ A and $I_{C2} = 47.6$ A.

Figure 9 shows the results of a TRANSPORT beam optics simulation of the above bump for C1 and C2 as run through the model of the Switchyard beamline. For every desired beam position at the MSeps, in 1 mm increments, a new TRANSPORT simulation was run with magnet bumps following the above calculation, and Figure 9 shows the resulting beam position through the MSep region as a function of desired position. We can see that the calculated bump angles provide consistent parallel beam through the septa with the desired control of beam position. Current in the C3 and C4 correctors downstream of the MSeps will be adjusted as free parameters to fine-tune losses on the septum and angles into the Meson and NM beamlines.

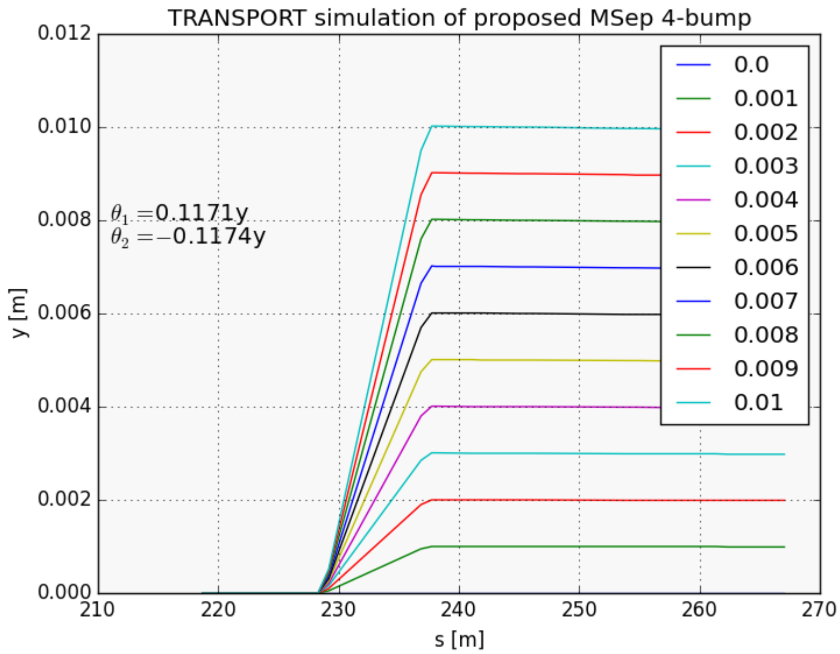

Figure 9. TRANSPORT simulation of bump.

Conclusion

It has been shown that a four-bump method for changing the split ratio between Meson and Neutrino-Muon beamlines will provide more control over losses from the MLAM septum aperture restriction. The current method of moving the MSep tanks alters the symmetry of the split with respect to the MLAM septum, increasing the amount of beam that hits the septum. Consistent operation of this scheme will require use of the new resonant BPM system in conjunction with an auto-tune program.

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